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HOW PLANTS REGULATE HEAT

Biomimetic Inspirations for building skins

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Abstract. Biomimicry is an approach that provides inspiration for answers to human problems by observing and analyzing nature's designs and processes. This paper addresses the problem of thermoregulation of building skins and their effects on cooling loads. These loads are an essential contribution to building energy consumption in hot climates. This research has turned to biology and focused on botanical inspirations for designing building skins. Plants in particular have many similarities with buildings, most importantly, that they are rooted and fixed in their location, and therefore were chosen for this investigation. The aim of this paper is to define a set of biologically-inspired ideas and categorize them according to the main strategy used, the method of heat transfer, and the corresponding architectural feature of the building skin that could be studied. It acts as a small 'concept database' and a systematic categorization of ideas for architects interested in biomimetic design.

Keywords. Biomimicry; thermoregulation; building skin.

1. Introduction

One of the key considerations in designing energy-efficient buildings is their skin. This element has the capability of improving the building's performance in natural ventilation, managing heating transfer, redirecting and filtering daylight and enhancing occupant well-being among several other functions. Therefore it could play an important role in reducing the energy consumed in cooling loads.

The motivation arose to investigate new design ideas for building skins that could help solve these kinds of problems. Turning to nature and biology was chosen for this investigation, since nature possesses a '3.8 billion-year' history of experience, where much of the problems we face today have already been addressed and solved in more effective ways by natural organisms.

> "…it is biology, of all sciences, which first confronted the central problem of design in nature; and it is very natural that of all sciences it should for this reason attract the special interest of designers." (Steadman, 2008)

This paper aims to demonstrate a number of strategies used by plants for thermoregulation. These strategies are then categorized based on the main principle of heat transfer which helped in defining the possible architectural feature to study for each strategy. It serves as a list if ideas related to thermoregulation to be used by designers interested in this biomimetic design approach.

2. Design process

This paper is a part of an ongoing doctorate research in which the aim is to couple biologically-inspired ideas with computation through a performative design perspective. Authors published previous work focusing on explaining this suggested biomimetic-computational design methodology in detail (El Ahmar, et al., 2013) highlighting its benefits. This paper represents the initial phase of applying this design approach in an attempt to explore its potential by practical implementation.

There are generally two main approaches to biomimetic design; a Problem-Based and a Solution Based approach. The two approaches have been addressed in literature such as Zari (2007), Knippers (2009), Helms et al. (2009), and Biomimicry 3.8 (2012). This paper follows the first approach where the design problem addressed is thermoregulation of a building skin for hot climates.

In order to effectively search for ideas in nature, the design problem must be as specific as possible. The exploration began asking the questions of: how do plants minimize heat gain and/or maximize heat loss? The intention is not just to mimic what an organism looks like, but rather how its form or behaviour serves its needs to survive. The ideas found are then abstracted to understand the main underlying principle behind each of them. The design process followed in this research could be simplified in Figure 1.

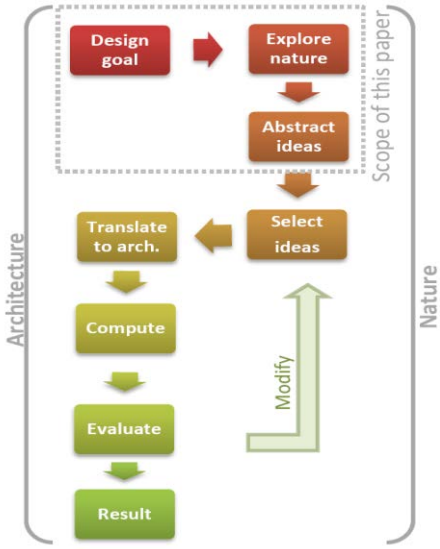

Figure 1: Biomimetic-computational design process followed in this research. The scope of this paper is outlined by dotted lines.

With the aim of reducing heat gain and consequently improving thermal comfort and reducing cooling loads, the physical processes of heat transfer were selected for further study to address this aim. Heat generally transfers through four main strategies which are radiation, conduction and convection (Allen, 2005). In case of living organisms, the fourth strategy (which is related to phase-change of matter) is evaporation (Mazzoleni and Price, 2013).

There are numerous building features that affect heat gain and loss, this research will focus only features related to the building skin. Listing each method of heat transfer with the main building skin elements that are related to it (Table 1) was important to serve as the bridge that links ideas from nature to its corresponding architectural element.

Table 1: Heat transfer processes and the influencing building skin features.

Radiation	Conduction	Convection	Phase-change
•Size/shape / location of openings •Shading elements •Skin overall morphology •Reflectance/ emittance of outer material	•Thermal resistance (insulation) •Thermal capacity •Materials' thickness •Materials' arrangement	•Ventilation system •Size of openings •Location of openings •(De)Humidification	•(De)Humidification •Ventilation system •Permeability of building skin materials •Phase-change materials

3. Plants as thermoregulators

Climatic conditions have an important influence on the forms and functions of living organisms that evolved as means of survival. Trees and plants are flexible structures that are sensitive to climatic conditions and as a response; they have evolved a number of techniques and features that aid in overcoming such situations. A focus here will be made on features developed in relatively hot environments. These features aid in thermal regulation either by minimizing heat gain, or maximizing heat loss.

In the following section, leaves, tree barks and succulents will be addressed and analysed to explore some of the strategies which they have in general to aid in thermal regulation.

3.1. LEAVES

Leaves are biological entities that are extremely differentiated, either on the level of different species, or even within the same one. The huge variation of shapes and sizes of leaves have long been a topic of research, indicating that it is a part of an adaptive response to different climates, and different microclimates within the same tree or plant (Schuepp, 1993). They only absorb the energy required for photosynthesis (which occurs within a temperature range between 30 and 40 degrees Celsius) and the energy required for the tensile water transport upwards along tree barks (Henrion and Tributsch, 2009), (Zähr, et al., 2010).

Comparisons have been made between sun and shade leaves of species in North America, and it was found that sun leaves have features that resemble those of leaves locates in hot habitats and therefore will be presented:

3.1.1. Size

Smaller and narrower leaves have evolved as they have a thinner boundary layer (a thin layer of air that does not move due to surface friction) and therefore less resistance and more heat loss by convective dissipation. For example, it has been found that warm environments and seemingly still air, broad leaves could reach 20°C above ambient temperature while relatively smaller conifer leaves (such as pine, spruce and fir) reached only 10°C (Vogel, 2009).

3.1.2. Shape

The shape of the leaf also has a role, as temperature on a given point on a leaf increases approximately with the square root of the distance from an edge (Vogel, 2009). So this distance decreases if a leaf is lobed (Figure 2), dissected or pinnate and narrow in addition to being smaller in size. Lobes and serration in leaves decrease the boundary layer resistance and improve free convection (convection not induced by wind) (Schuepp, 1993).

A trick that un-dissected or un-lobed leaves have evolved by time to overcome excessive heat gains in the summer is producing phytochemicals which lures certain types of insects to produce non-lethal holes in its blade. These holes permit buoyancy-driven convective airflow across rather than around the leaf (Schuepp, 1993).

Another observation regarding the form of leaves is that some have evolved a folded form that enables young leaves to fit inside small buds. This form allows self-shading and hence reduces heat gain. There are numerous folding patterns in plants (Patil and Vaijapurkar, 2007); among the well-known is common beech (*Fagus sylvaticus*) and hornbeam (*Carpinus betulus*) leaves.

3.1.3. Leaf surface

Another way of reducing incident radiation is by decreasing absorptivity. Silvery and shiny leaves have around 20% less absorbance than others (Nobel, 2005 in Vogel, 2009). Thus the presence of a waxy coating for reflection proves useful. Pubescence (leaf hair) has been observed as a feature (Figure 2) of plants in arid climates, because they reduce the heat load of leaves by increasing the reflectance from the leaf surface which reduces amount of radiation absorbed (Ehleringer, et al., 1976).

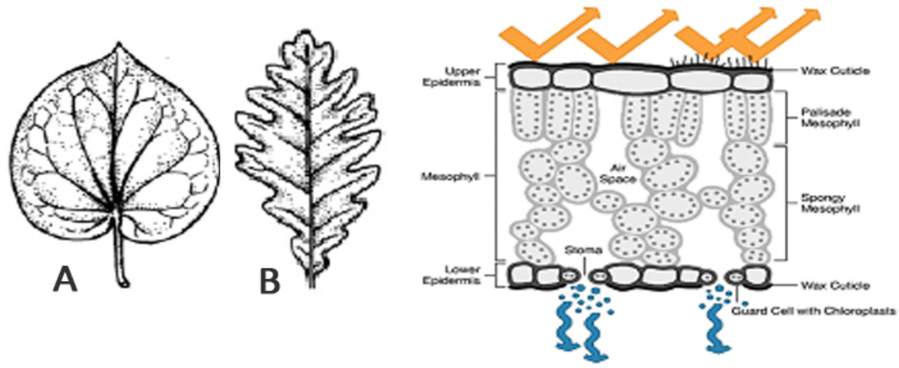

Figure 2: (left) difference between a cordate leaf (A) and a lobed leaf (B). Lobes improve free convection. Image source: The vPlants Project (2009). (Right) Schematic cross-section through leaf indicating a reflective upper surface either by was or pubescence to minimize incident radiation. Stomata openings in the lower side responsible for evaporative cooling.

Stomata distribution is another very important aspect that leaves have evolved, since sun leaves general have more stomata per unit area than shade leaves (Vogel, 2009). Increased stomata mean better heat loss through transpiration; it has been observed that sun leaves could transpire up to 12 times faster than shade leaves. This feature is particularly important in the case of very low speed of air movement where free convection becomes dominant (Schuepp, 1993). However, it is only beneficial in (relatively) water/moisture abundant environments where plant can afford to lose water to cool through transpiration.

3.1.4. Orientation

The effects of changing orientation are usually seen in un-lobed leaves. They tend to avoid near-horizontal positions reduces incident radiation in addition to improving convection between the leaf blade and surrounding air. Mangrove leaves are a good example where sun leaves are almost vertical while shade leaves are almost horizontal. Some leaves are capable of rotating throughout the day to adjust their position and reduce heat gain such as the *Alibizzia* (julibrissin) leaves (Vogel, 2009).

3.1.5. Venation system

Venation systems have two main functions which are transporting substances from one point to another with the least investment in energy and mass and sustaining the mechanical behaviour and structural support of leaves (Kull and Herbig, 1994; Nebelsick, et al., 2001). However, here the authors are interested in the contribution of venation systems to the thermoregulation of leaves, as they transport water which is vital for cooling by transpiration.

The wide variety of venation patterns imply a strong evolutionary selective process, however the functional background of this variety is still not well understood (Nebelsick, et al., 2001; Sack, et al., 2012). Nevertheless, studies addressing this issue show general differences between sun leaves vs. shade leaves within same species, and between leaves in hot climates vs. temperate ones. These observations are summarized as follows:

Regarding the venation type; closed venation systems occur more frequently than opened ones (Figure 3) in areas with less water availability than others. This could be due to many reasons such as the availability of multiple paths to reach a certain point so the water could take the shortest possible one. Another reason is the increased safety if compared to open systems, so if one path is damaged due to injury then water and other substances could still reach areas beyond the damaged route due to the existence of other alternative bypasses. A third reason is the capability of providing homogeneous pressure difference across a leaf in the case of varying stomatal opening degrees and varying transpiration rates (Nebelsick, et al., 2001).

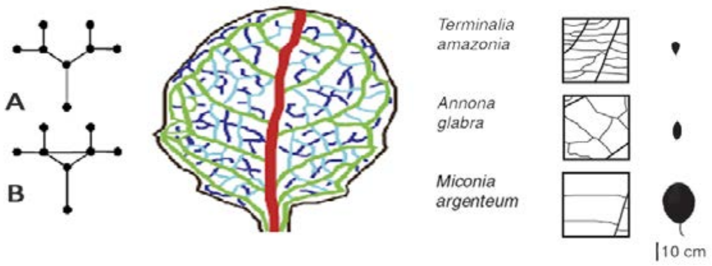

Figure 3: (Left) Types of venation systems; open (A) & closed (B) (Nebelsick, et al., 2001). (Middle) Diagram illustrating orders of veins. Red: 1º, Green: 2º, Cyan: 3º, Blue: 4º. The first 3 degrees are the ones considered major veins. (Right)Decrease of major vein density with the increase of leaf size (Sack, et al., 2012).

Regarding venation density and radii; studies have shown that with decreasing leaf surface area (as seen in sun leaves and in hot climates) the diameters of only the *major* veins (Figure 3) decreases, but their density increases (density= vein length per unit area), minor vein however are independent of leaf size. Smaller diameters come with less vascular costs to construct them, and higher densities provide a redundant 'super highway' system for water transport which contributes to drought tolerance by easily routing water around blockages caused by drought and protecting the overall hydraulic system from vein damage (Sack, et al., 2012; Kull and Herbig, 1994).

3.2. TREE BARKS

Tree barks have always attracted people attention due to their appearance, and despite their diversity that make it seem difficult to find common thermal regulation strategies, they all serve the function of efficiently delivering cool water to leaves. Unlike leaves, barks are not capable of cooling by evaporation. Therefore they have evolved other strategies to remain cool (Henrion and Tributsch, 2009). They include morphological ones such as:

- They are usually round, which means they have the minimum exposed surface area to incident solar gain and surrounding temperature thus preserving its own internal temperature as much as possible.
- They have a very thick insulating outer layer, which in some cases to reach 50 cm in thickness (as in sequoia barks).
- Some trees have developed rough bark textures that provide shaded areas thus decreasing the heating effect of incident light (Figure 4).
- Other barks that are not very thick, have evolved to have an outer layer that peels off like paper, creating air gaps that improve insulation and reduce heat gain by conduction.

In addition to these morphological features, it has been noticed that there are features regarding the reflectivity and emissivity of tree barks. An experiment has been done by Henrion and Tributsch (2009) where they found that tree barks are optimised not for reflecting the visible spectrum of solar light (of wavelengths between 380 and 750 nm), but rather for the filtered (transmitted) and reflected light from surroundings (which is a part of infrared light of wavelengths of 700 to 2000 nm). This is particularly important since in most cases the light that reaches tree barks is either solar light reflected from surrounding vegetation or light that has been transmitted through thin leaves of the same tree.

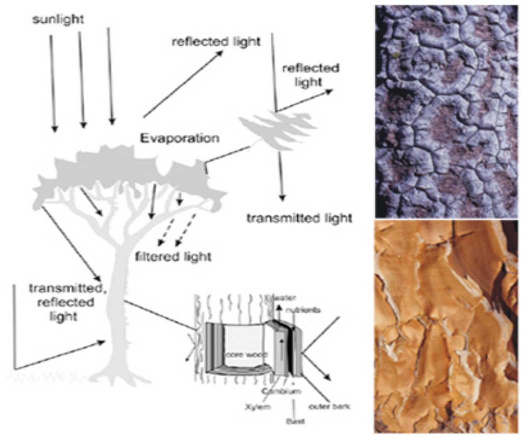

Figure 4: (Left) Drawing of crown, leaves, and bark of a tree visualizing their involvement in optical atmospheric processes. (Right) Different bark morphologies. (Auracariaauracana; top, & Aloe dichotoma; bottom) (Henrion and Tributsch, 2009).

3.3. SUCCULENTS

A number of strategies that desert succulents use for thermal regulation are mentioned as follows (Hadley, 1972; Jones and Rotenberg, 2011):

The relationship between surface area and volume is one of the important factors that determine the rate of heat transfer between the organism and its environment. Heat transfer through radiation, convection and evaporation is proportional to the surface area of a plant or animal. Since small organisms have relatively big surface area to mass ratio, their temperature increase and decrease more rapidly and are easily influenced by surrounding temperature. Some large succulents use this concept to their advantage and have a small area to volume ratio such as prickly pear (*Opuntia littoralis*) and barrel cacti, so they heat up more slowly.

Many succulents close stomata during the day and open them at night when the temperature has decreased and relative humidity has increased to decrease water loss by transpiration. In this case the process of photosynthesis occurs at night as carbon dioxide is absorbed and combined with an acid in a process called Crassulacean Acid Metabolism (CAM).

The concept of self shading is widely used among succulents. Varying from spines and protrusions, ribbed surfaces, grooves, or smooth alternating concave and convex surfaces such as in Senita (*Cereus schottii*). These seeming irregularities decrease the incident angle of solar radiation as well as reflect and scatter part of it. Those which have hairy spines help also collect dew droplets (Figure 5) and funnel them down the grooves to combine with other droplets forming bigger ones and decreasing their chances of being lost by evaporation.

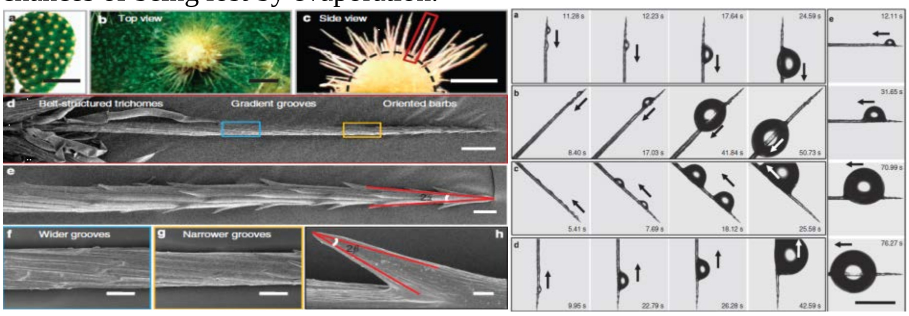

Figure 5: Cactus surface structures (Left). Microscopic observation of the water collection on the cactus spine placed at various angles (Right) (Ju, et al., 2012).

4. Observations

This paper presents investigation into natural organisms and the various means by which they achieve thermoregulation. The ideas presented are by no means all of those available in the plant kingdom. They only represent what the researcher has investigated up to this date. In order to proceed in the biomimetic design process, the architectural equivalent (building skin feature) of each strategy must be specified as shown in Table 2.

It is observed that numerous strategies focus on thermoregulation specifically by minimizing the heat gained due to incident solar radiation. This indicates the important role of morphological aspects and surface properties of the organism in its adaptation to hot environments, and consequently the morphological and surface properties of the building skin as well.

It is also noticed that some architectural features (such as morphology, shading elements and cladding materials) could have more than one possible biomimetic strategy. It is therefore necessary to undergo a selection process and choose the ideas that would be further explored. The criteria on which we should base the selection could be:

- Available technology and materials.
- Construction and maintenance costs.
- Designer and client preferences.
- Coherency/contradiction of the selected idea with others.
- Multi-functionality of the idea; whether it has simultaneous benefits such as structural, environmental, or aesthetic advantages.

Table 2: Summary of investigated strategies so far and the corresponding building skin features to study, categorized according to the four heat transfer methods.

MINIMIZE HEAT GAINED BY RADIATION		
Organism	**Strategy**	**Arch. Feature**
Leaves	Folds	Overall Morphology/Shading elements
	Avoid horizontal position	Overall Morphology/Shading elements
	Shiny surface	Cladding material
	Pubescence	Cladding material
Barks	Round cross-section	Overall Morphology
	Rough surface	Cladding material
	Reflection of non-visible light spectrum	Cladding material
Succulents	Ribs and grooves	Overall Morphology/Shading elements
	Spines and hairs	Cladding material
	Alternate curves	Overall Morphology/Shading elements
MINIMIZE HEAT GAINED BY CONDUCTION		
Organism	**Strategy**	**Arch. Feature**
Leaves	X	X
Tree Barks	Thick outer layer	Insulation/Cladding material
	Peeling surface	Overall Morphology/Cladding material
Succulents	S/V ratio	Exposed surface area
MAXIMIZE HEAT LOST BY CONVECTION		
Organism	**Strategy**	**Arch. Feature**
Leaves	Small narrow sizes	Shading elements
	Lobes and dissections	Perforations
	Holes and tears	Perforations
Tree Barks	X	X
Succulents	X	X
MAXIMIZE HEAT LOST BY EVAPORATION		
Organism	**Strategy**	**Arch. Feature**
Leaves	More/bigger stomata	Ventilation system
	Closed, dense venation system	Ventilation system
Tree Barks	X	X
Succulents	Spines collecting water droplets funnelled through grooves	Ventilation system

It is beyond the scope of this paper to illustrate architectural design ideas for each biomimetic strategy presented, however a couple of general examples could be mentioned in order to put some of these ideas within an architectural context. For example, the overall morphology of the building skin could be designed using a panelling system where each panel would take a slightly different orientation depending on the amount of incident radiation falling on it. On a micro scale, the surface properties of these panels could have a rough texture to diffuse incident light and provide self-shading. This panelling system could be just an outer surface of a multi-layered skin that provides high insulation values and reduces the heat gained by conduction.

The structure supporting this skin would be a hollow branched system effectively bearing loads and at the same time acting as ventilation ducts delivering cool air to different building zones.

In order to continue this investigation, the authors chose one of presented ideas, which is the concept of folding (seen in some leaves and cacti) to proceed to the next phase of the biomimetic design process. Folding ideas served as a basis for studying the morphology of a proposed skin for an office building in a hot climatic country. The design was made using computational software and assessed using environmental simulations to evaluate the skin's performance regarding thermoregulation. The resulting work represented the scope of another paper published by the authors (El Ahmar & Fioravanti, 2014). Future work includes more detailed design of the building skin, studying its structure, natural ventilation and overall behaviour.

Biomimetic building skins can be found in both academia and, less commonly, in professional practice. Examples can also be found in research projects in the AA School of Architecture in London, the ICD in Stuttgart University the Austrian Institute of Technology, and in the MIT Media Lab among many others.

5. Conclusion

Biomimetic design is becoming more and more popular across many fields of study due to its potential benefits, and the field of architecture is no exception. Addressing the problem of increasing cooling loads in hot climates, this paper represents an investigation into plants to learn from them how to minimize heat gain and/or maximize heat loss in hot climates.

A number of strategies has been found and simplified to understand the underlying concept and the main heat transfer method in order to effectively study the corresponding architectural equivalent of each one. These strategies have been listed in Table 1 and categorized with respect to the method of heat transfer. The table could be re-categorized based on the architectural features, or based on the organisms themselves. It acts a mini 'concept-database' for designers aiming to solve cooling problems related to the building skin. This paper represents the initial phase of this biomimetic design approach and is a part of ongoing doctorate research.

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